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Wideband metamaterial-based array of SINIS bolometers

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Introduction

Recently we have developed and experimentally studied a wideband 2D-array of periodically arranged electrically small rings, each containing Superconductor-Insulator-Normal metal-Insulator-Superconductor (SINIS) bolometers. Earlier such bolometers in a regular annular antenna array [1] demonstrated voltage responsivity up to 10^9 V/W with a bandwidth of 5-10% in a 350 GHz frequency band. Such detector array can operate in background noise limited condition for incident powers up to 80 pW [2,3]. The typical diameter of the rings was $\lambda/2$, where λ is an effective wavelength on the silicon-vacuum interface related to free-space wavelength λ_0 by

$$\lambda = \frac{\lambda_0}{\sqrt{\frac{\epsilon+1}{2}}} \qquad (1)$$

Wavevector **k** of a normally incident plane wave has zero tangential component. For this reason a periodic array with the elementary unit cell size of the order of λ is seen by a normally incident plane wave as a homogeneous thin film with effective impedance Z_{FSS}. The condition of normal incidence is satisfied in quasioptical systems when the detectors array is placed into the focus of a lens where the wase of the Gaussian beam is. Large spatial period of the array reduces the operational frequency bandwidth. In the present work we report on the studies of the wideband array of cold-electron bolometers designed for the range 300-450 GHz and consisting of periodically arranged rings, each containing four bolometers. This periodic array with the unit cell size less than $\lambda/10$ acts as a distributed metamaterial absorber, which is seen as homogeneous metamaterial film by the wave incident at any angle. This fact makes the array applicable for integration into waveguides where all three orthogonal k-vector components of the propagating wave are nonzero. Small unit cell size ensures higher density of bolometers and therefore increases the bandwidth and the dynamic range of a single pixel.

Numerical model and optimization

The chip with a wideband array is designed for mounting on a silicone lens similar to integrated lens antennas. Figure 1 shows a layout of the unit cell with dimension 37um x 38 um in XY plane. A structure made of golden thin film is fabricated on a silicone substrate and the four cold-electron bolometers are integrated into it. The Floquet ports are placed at the boundaries corresponding to the minimum and the maximum of z-coordinate.

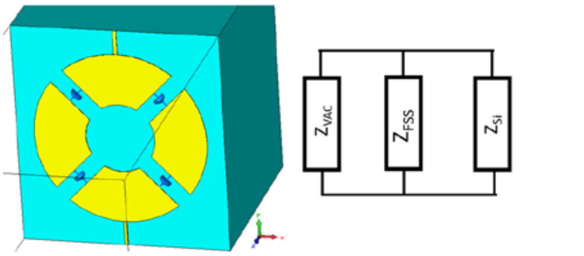

Fig.1. Unit cell design and the lumped elements equivalent schematic

Most of the RF-power coming from the silicone lens is absorbed by the SINIS-bolometers, but some fraction of it is transmitted further into the vacuum half-space because of no backshot. The equivalent microwave schematics of this setup can be represented as a parallel connection of the three lumped impedances: surface impedance Z_{FSS} of the array is shunted by impedance Z_{VAC} = 377 Ω and Z_{SI}=377/√11,7 Ω of vacuum and silicon half-spaces. From this simple schematic one can derive the following formula for the power P_{abs} transmitted from Z_{SI} to Z_{SI}:

$$P_{abs} = \frac{Z_{VAC}}{Z_{FSS}+Z_{VAC}} \cdot \frac{4Z_{SI}Z_{VAC}Z_{FSS}(Z_{FSS}+Z_{VAC})}{(Z_{SI}Z_{FSS}+Z_{SI}Z_{VAC}+Z_{VAC}Z_{FSS})^2} \qquad (2)$$

Dependence of P_{abs} as a function of Z_{FSS} is plotted in figure 2. It achieves maximum P_{abs} = -1 dB at $Z_{FSS} \approx$ 80 Ω. This value of Z_{FSS} is slightly less than that of parallel connection of Z_{SI} and Z_{VAC}.

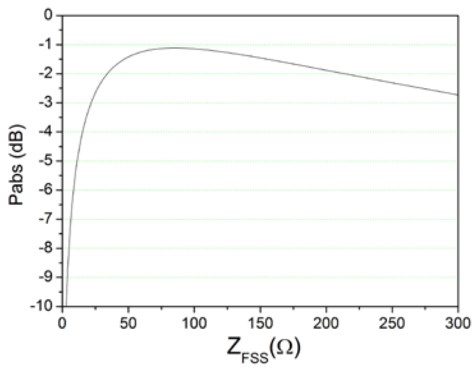

Fig.2. Absorbed power P_{abs} as a function of Z_{FSS}. Maximum P_{abs} corresponds to $Z_{FSS} \approx$ 80 Ω

During numerical simulations we considered the two lowest port modes with orthogonal polarization and constant distribution of the electric and the magnetic fields. The the E-field of the first Y-polarized mode is directed along the narrow DC-biasing lines that connect adjacent unit cells together and create series inductance, which tunes the capacitance of the SINIS-bolometers out. For the second X-polarized mode Z_{FSS} is determined by the planar capacitance between the rings of the adjacent unit cells.

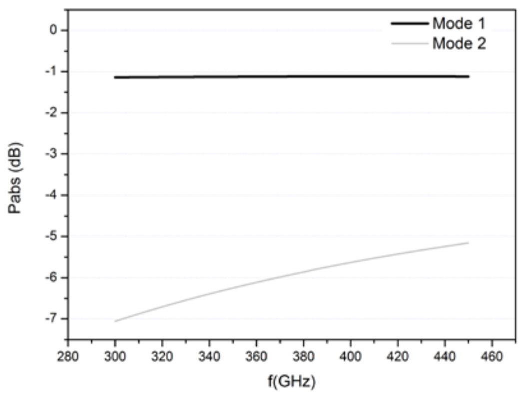

Fig.3. Simulated absorbtion P_{abs} of the SINIS-array fo the two modes with orthogonal polarization

Figure 3 shows the simulated absorbtion of both modes for the array with the optimized unit cell design. and the optimal capacitance C=20 fF and the resistance R=100 Ω of each SINIS-bolometer. According to numerical simulations based on the FDTD-method P_{abs} for the first mode is expected to be close to the -1 dB limit in the whole frequency range 300-450 GHz as like it was predicted by formula (2). The capacitive reactance of the bolometer array seen by the second mode results in much lower P_{abs} ranging from -7 dB to -5 dB.

Experimental test

During experimental tests the spectral response of the sample with the array of SINIS-bolometers was measured in He3 sorption cryostat with optical window and a set of cold neutral density filters that were acting as cold attenuators to reduce the power of room temperature background blackbody radiation. A tuneable external narrowband submm source of radiation was illuminating the 10x10 unit cells array that covered the Airy spot in the focus of the lens. An additional absorber was placed behind the array at some distance from the vacuum side to get rid of the standing waves and make more uniform and wideband frequency response characteristics. The experimentally measured spectral response in the range 240-370 GHz is shown in figure 4. The response is wide and quite nouniform. The nonuniformity may come from the standing waves existing between the cold neutral sensity filters and optical windows. Also the spectral response can be influenced by spurios reflections from some parts of the mesurement setup close by the sample holder.

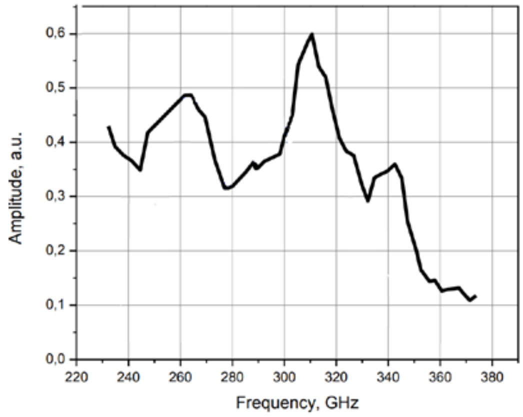

Fig.4. Experimentally measured spectral response of the SINIS-bolometers array

From the measurements with a blackbody source The voltage responsivity of the array with 100 rings measured from a blackbody source was as much as $1.3*10^9$ V/W

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